Calculation of Blast Loading in the High Performance Magazine with AUTODYN-3D

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Abstract:

The High Performance Magazine (HPM) is being developed by the Naval Facilities Engineering Service Center (NFESC) to reduce the land area encumbered by Explosive Safety Quantity Distance (ESQD) arcs and improve the efficiency of weapons handling operations. In the past, testing has been required to obtain verification and acceptance of designs to prevent sympathetic detonation. Due to the numerous possible configurations and ordnance storage layouts, the development and verification of prediction models is critical.

AUTODYN-3D, a non-linear dynamics software program, is used to calculate the detonation of various configurations of stored ordnance in the Certification Test Structure. AUTODYN models the initial detonation, blast, and loading on the surrounding structures providing a detailed time-dependent three-dimensional view of the accident scenario. Pressure and impulse histories at selected locations as well as structural displacements and velocities are shown. Advantages and limitations of the numerical methods utilized within AUTODYN-3D are discussed.

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1. Introduction.

AUTODYN-3D, a commercially available hydrocode, was used to model five different accident configurations in the High Performance Magazine (HPM) Certification Test Structure. The numerical models and techniques used to simulate the highly non-linear explosive detonation, blast and loadings on the structures are discussed. The detailed three dimensional calculations provide results to allow accurate determination of the safety of the proposed design. Results of the calculations are compared for the different accident scenarios. An animated sequence of the explosions and resultant blast loadings was created.

2. Description of the model:

The weapons storage area of the HPM consists of two 82' L x 20' W x 15.5' H storage pits separated by a transfer aisle wall. AUTODYN-3D was applied to the Certification Test Structure #1 which models one of the two weapon storage areas of the HPM. Figure 1 illustrates the plan view of the model configuration.

Figure 1. Basic Model Configuration, Plan View

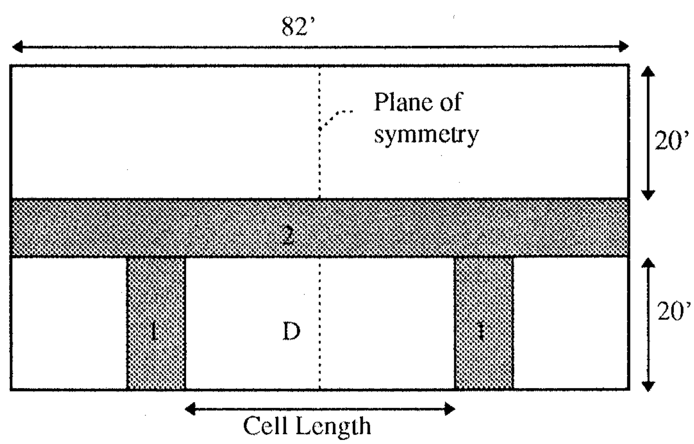

Figure 1. Basic Model Configuration, Plan View

The elements of the model are the relocatable walls (1) , aisle wall (2), and the donor cell (D) where the weapons are stored. Five different configurations of the donor cell length and explosive charge weight are analyzed:

CASE	Explosive Weight	Donor cell length
1	30000 lbs	38.5‘
2	20000 lbs	38.5’
3	30000 lbs	51’
4	20000 lbs	51’
5	16000 lbs	26’

TABLE 1.

The initial donor cell length is controlled by the placement of the relocatable wall. The relocatable wall and aisle wall are not structurally connected. Therefore the relocatable wall is allowed to slide freely along the aisle wall. None of the structures are anchored to the surrounding walls. Rigid walls are assumed at the bottom and sides of the HPM configuration. The roof of the HPM is modelled as a deformable structure with a free top surface.

The stored weapons are modelled with an equivalent weight of TNT. The explosive weight is divided into 24 individual spherical sites within the donor cell with the assumption that all sites are detonated simultaneously. Essentially two layers of 12 sites near the bottom of the donor cell are used, simulating a stacked storage configuration of the weapons.

The model shown in Figure 1 has a plane of symmetry which allows “half” of the problem to be modeled by using a rigid wall at the plane of symmetry. This decreases the size of the required numerical model by half thereby also decreasing the computational time required.

Figure 2. AUTODYN-3D initial numerical mesh.

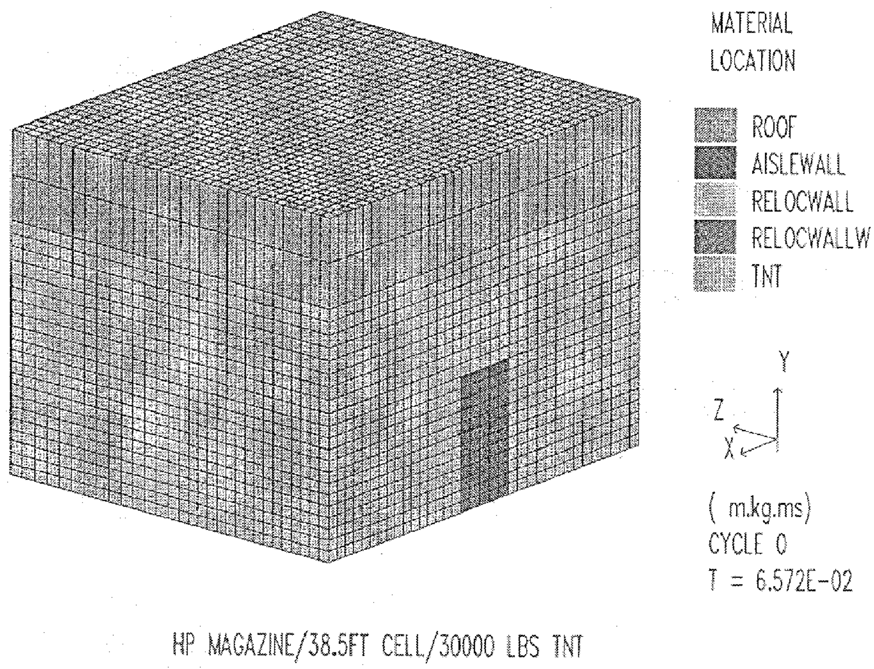

Figure 2. AUTODYN-3D initial numerical mesh.

The size of the numerical mesh is 36 x 24 x 31 (IxJxK) for a total of 26784 cells as shown in Figure 2. This resolution will provide adequate results for the motions and deformations of the walls. Peak pressures measured on wall faces will, of necessity, be resolved across a rather large cell thereby reducing its absolute value. However, the impulse delivered to the structures will be accurate. More cells could be used, but a increase in cell resolution by a factor of two increases the number of cells by a factor of 8 and decreases the timestep by a factor of two. Thus, the calculations would run 16 times longer.

The numerical mesh defines a system 14.478 x 11.582 x 12.497 meters or 47.5 x 37.8 x 41 feet with a plane of symmetry at Z=0. and fixed walls at all other locations except the roof top which is free. The system of units used is kg, meter, millisecond. This yields pressures in kilopascals and velocities in meters/millisec.

The equation of state for the relocatable wall, aisle wall, and roof is specified as “sand” with various densities to model the actual areal densities for the HPM prototype. The Appendix outlines the various material constants and areal densities used. Figure 3 shows the location of the various structures within the numerical mesh with the surrounding air and TNT not depicted. A layer of cells between relocatable wall and the aisle wall is specified to have no strength to simulate the free sliding condition (material name: RELOCWALLW).

Figure 3. Location of structures within AUTODYN-3D mesh

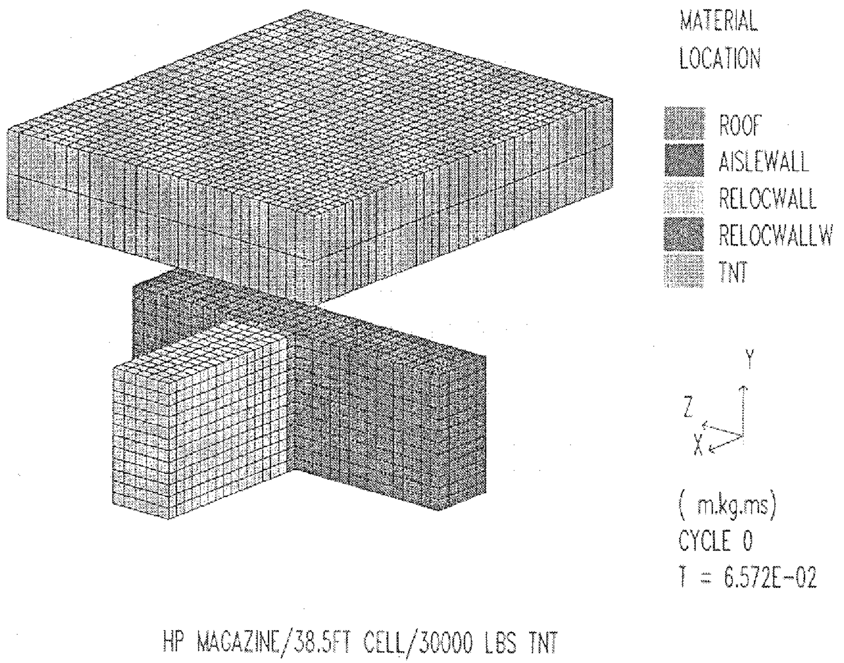

Figure 3. Location of of structures within AUTODYN-3D mesh

The equation of state for the TNT and air utilizes the well characterized Jones-Wilkins-Lee model (Ref. 1). Since the TNT explosive sites are modelled as spheres, a finely zoned one-dimensional calculation, using AUTODYN-2D, is used to model the initial detonation and buildup of the detonation wave. Using a standard feature of the AUTODYN programs this one-dimensional simulation is then mapped into the three-dimensional model as an initial condition for the 3D calculation (Ref. 2). The one-dimensional solution is only valid until the explosive sites start to interact with each other or the surrounding structures. The advantage of this 1D to 3D remapping technique is that it allows a much more accurate description of the detonation than could practically be achieved in a 3D numerical mesh. The initial conditions of the air are set to yield an initial 1 bar (100 kpascals).

Note that JWL equation of state was used for both the TNT and air. The JWL equation of state for large expansions acts as an ideal gas. Thus, the air is modelled as very expanded TNT with an ideal gas constant of 1.35. This corresponds to the W factor = 0.35 in the JWL equation of state. The TNT and air are thus modelled as a single material with very different initial conditions for density and energy.

The explosive sites for CASE 1, created using the remap capability, are shown in Figure 4. The initial time of the 3D calculation is set to the termination time of the 1D detonation problem (~ .06 msecs).

Figures 4. First and second layer of explosive sites

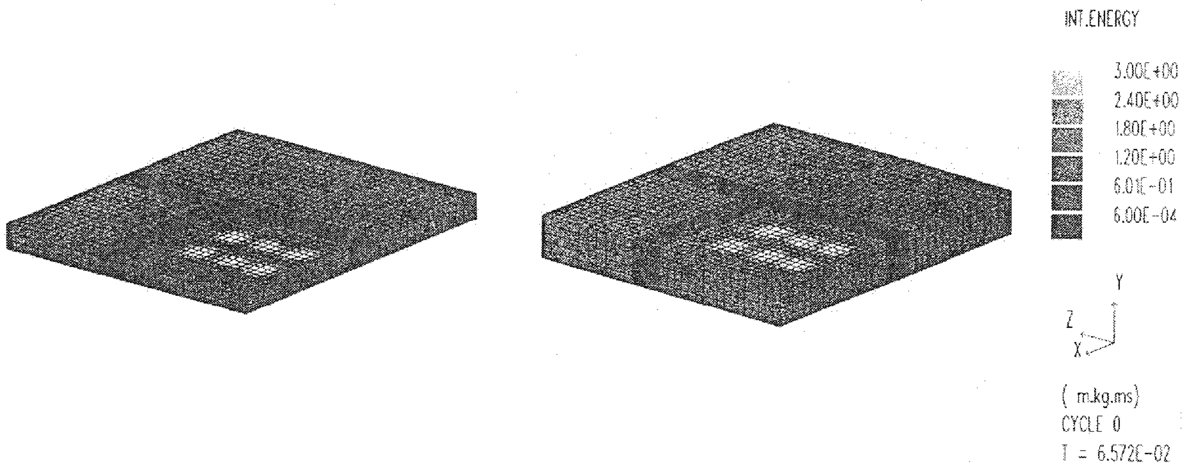

Figure 4. First and second layer of explosive sites

The analyses were all carried out to a problem time of 30 milliseconds at which time the peak pressures and impulses have been experienced. At this time the accelerations of the relocatable and aisle walls have also subsided.

3. AUTODYN-3D description:

AUTODYN-3D is a fully three-dimensional explicit finite difference program which can utilize a number of different numerical techniques to optimize the analysis of non-linear dynamic problems (Ref. 3). The time-dependent solution is developed as a sequence of cycles or timesteps. The timestep in this explicit integration code is automatically controlled to maintain stability of the calculation.

AUTODYN-3D allows different numerical techniques to be applied to the different regimes of a problem to provide an optimal solution. Most analysis programs are typically either a structural type program or a fluids type program. The HPM analysis requires the ability to simulate both fluid/gas behavior as well as structural response. This coupled fluid/gas - structure interaction requirement is a specialty of the AUTODYN programs. AUTODYN can be described as several codes in one, encompassing gas, fluid, and structural behavior. AUTODYN incorporates a number of different numerical processors in the same program and allows them to dynamically interact with each other. Each of these numerical processors has certain advantages and disadvantages. A brief review of the numerical processors available in AUTODYN is presented:

Lagrange

In the Lagrange processor the numerical mesh moves and distorts with the material motion. The advantage of such a scheme is that the motion of material is tracked very accurately. Material interfaces and free surfaces are clearly defined. Also, history dependent material behavior is readily treated. The primary disadvantage of the Lagrange formulation is that for severe material deformations or flow the numerical mesh will also become highly distorted with attendant loss of accuracy and efficiency or outright failure of the calculation. Typically, a Lagrange formulation is best suited for structural materials but not fluids or gases.

Euler

In the Euler processor the numerical mesh is fixed in space and material flows through it. The advantage of such a scheme is that large material flows and distortions can easily be treated. The disadvantage of such a scheme is that material interfaces and free surfaces are not naturally calculated. Sophisticated techniques must be utilized to track material interfaces. Additionally, history dependent material behavior is more difficult to track. In general the Euler processor is also more computationally intensive than Lagrange. Typically, the Euler processor is best suited for fluid and gas behavior.

ALE (Arbitrary Lagrange Euler)

This is a hybrid processor wherein the numerical mesh moves and distorts according to user specification. At one limit, where the mesh is specified to move with the material motion, ALE reduces to a Lagrange formulation. At the other limit, where the mesh is fixed, ALE reduces to an Eulerian formulation. In between, ALE can be described as a type of Lagrange but with "automatic rezoning". The ALE processor coupled with Lagrange processors is used in the HPM calculations presented. ALE describes the TNT and air motions with Lagrange used for the structures.

Shells

For thin shell structures a special type of Lagrange formulation may be used which does not have the timestep restrictions normally associated with thin bodies. Shells were not required in the HPM analyses presented here.

Processor Coupling

Different numerical processors within AUTODYN-3D may be utilized in the same problem and coupled together automatically in space and time. In the HPM calculations, the early stages of the TNT expansion and resulting blast waves in air are characterized by extreme TNT and air motions. These are best modelled in ALE using an Eulerian (fixed mesh) specification. Later, after the initial stages, the ALE specification is relaxed to a more computationally efficient approach wherein the mesh is allowed to move as Lagrange with an occasional rezone to keep the mesh numerically efficient and accurate. The structures are modelled as Lagrange throughout the calculation allowing an accurate tracking of their distortion and translational motion.

<u>Practical Analysis Considerations</u>

Three dimensional calculations, such as those presented here can be generally characterized by the following:

1. Difficulty in setting up the numerical mesh, specification and verification of the initial conditions and material models.

2. Creation of massive amounts of output data

3. Requirements for substantial computer resources to perform the calculations.

While the above issues do not affect the physical aspects of the problem being analyzed they do have a significant effect on the ability of the analyst to correctly and efficiently setup, analyze, and understand the results of the analysis. These practical considerations are extremely important. Many large scale programs, while they may be otherwise be sophisticated in terms of material modelling or numerical techniques typically do a very poor job addressing these practical issues.

AUTODYN-3D, as a commercially available and supported software package, includes a number of features all designed to facilitate the entire analysis process:

- Graphical User Interface (GUI) : AUTODYN-3D utilizes an interactive menu-driven graphical user interface. An example screen is shown in Figure 5. A hierarchical menu structure leads the analyst through all features of the program. Context sensitive help screens are available at all times.

- Integrated Analysis Environment: Pre-processing, analysis phase and post-processing are all contained in a single program. There is no need to use different programs to setup models nor to display the results. All capabilities are included in a single program.

- Interactive Analysis: As the dynamic calculation proceeds, current results are displayed. The user may pause the calculation at any time and examine the results to that point in detail. Then, the analysis may be restarted and continued to a later time.

- PC and Workstation availability: AUTODYN-3D provides sophisticated and efficient calculational capability on PC’s, workstations, as well as supercomputers. The calculations presented here were performed on a standard Pentium computer without the requirement for an expensive high level computer.

- Compatibility from PC’s to Workstations: Data files are compatible from PC level to workstations up to supercomputers. This allows the analyst to optimize the solution procedure according to the available.computer facilities. For example, setup of problems and viewing of output on smaller machines can be accomplished with major number crunching performed on larger machines.

Figure 5. Typical AUTODYN-3D screen with interactive menu

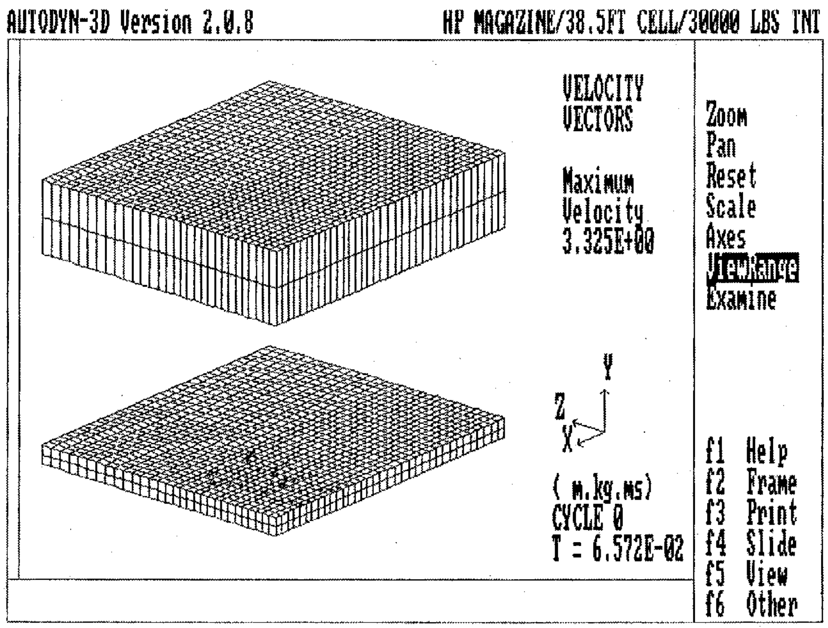

Figure 5. Typical AUTODYN-3D screen with interactive menu

4. Analysis Procedure

After the initial grid is established and filled with material and initial conditions using the 1D to 3D remap facility, a quick check is made using the various interactive plots and material summary information provided by AUTODYN-3D. Some of the issues quickly verified include:

Has the correct amount of initial energy from the explosive sites has been mapped into the mesh ?
Are the explosive sites located properly ?
Are the material models correctly specified ?
Are the boundary conditions correctly applied ?
Have the time history gauges been placed properly ?

The calculation is started. An ongoing display is updated as the calculation proceeds. A typical display is shown in Figure 6 . Only a "slice" of the mesh is shown so that we may view results "inside" the mesh. The user may specify any number of different types of display plots as well as the viewpoint from which to monitor the calculation. Typically, if an error has been made in the setup of the model it will become readily apparent from the ongoing display, allowing the user to correct the model and restart the calculation.

Figure 6. AUTODYN-3D display during calculation

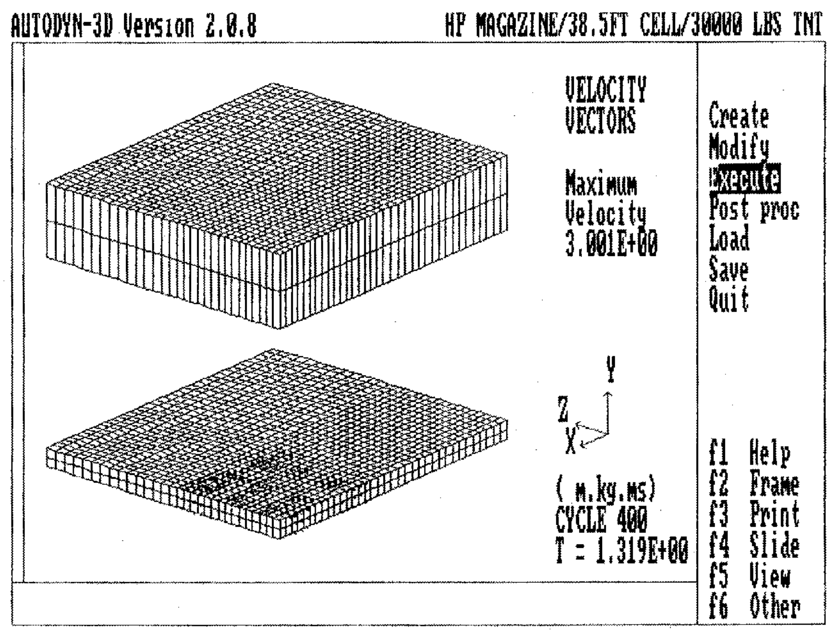

Figure 6. AUTODYN-3D display during calculation

Each calculation was started using the ALE processor in the TNT and air region with a fixed mesh (Euler) specified. Figure 7 illustrates the ALE motion constraints. After 1500 to 2000 cycles the Euler specification is changed to Equipotential wherein the mesh uses an equipotential algorithm to maintain a consistent and regularly spaced mesh. In these calculations the equipotential algorithm is specified to be invoked only every 10 cycles and then to only move a node 20% of the distance to the new position. This means that for 9 cycles a normal Lagrange motion calculation is used. In the tenth cycle a "rezoning" cycle occurs and then the rezoning is only "relaxed" by 20%. This provides a "gradual" smoothing of the numerical mesh avoiding abrupt changes.

Figure 7. ALE motion constraints at cycle 0

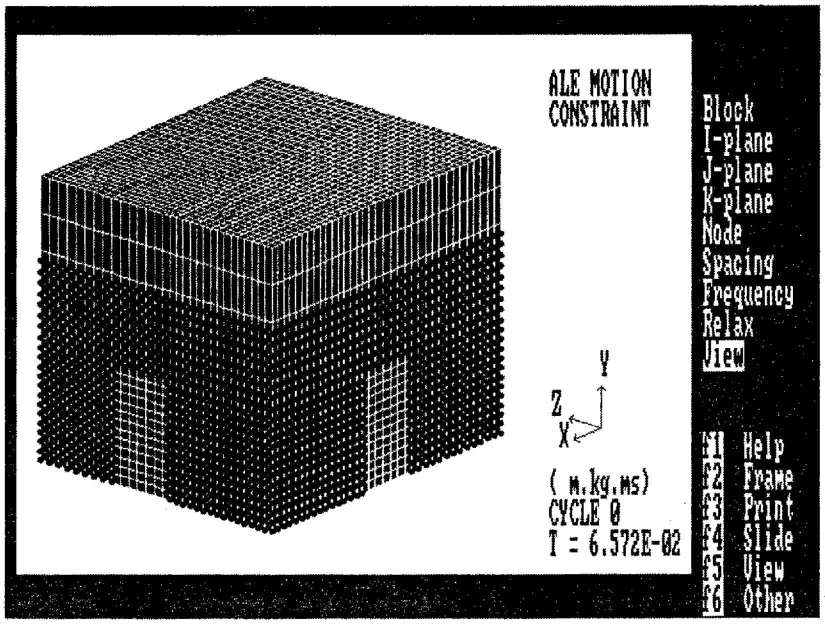

Figure 7. ALE motion constraints at cycle 0

As the relocatable wall translates in space under the blast loading, the donor cell region becomes expanded while the air space on the other side of the relocatable wall becomes reduced. The equipotential ALE motion specifications however maintain a regular mesh on both sides of the relocatable wall. The same issue occurs with the regions adjacent to the aisle wall in proximity to the donor cell. Using Euler(fixed mesh) alone would not properly allow the mesh to contract and expand. Using Lagrange alone would cause certain cells to become overly compressed or expanded. Use of the ALE processor for these calculations allows for both the extreme gas movements against and around the structures while coupled to the Lagrange processor for the structural elements.

The calculations run unattended with no user intervention required after changing the ALE specification from Euler to Equipotential after the initial 1500 cycles. Each calculation was run to a problem time of 30 milliseconds (~7000 cycles). On a Pentium 90 computer, each calculation requires ~50 hours of computational time.

Complete data is saved every 200 cycles to allow for later post-processing. For each calculation ~40 gauge locations are specified. At each gauge location time history variables are saved every 2 cycles providing sufficient time points to produce detailed history plots.

Disk storage requirements for each case are ~100 megabytes.

5. Results

Selected results for the five cases are shown in Figures 8 to 16. AUTODYN-3D includes the ability to combine the data from several analyses in a variety of different ways. Shown are the "normal" momentum of the relocatable(Z-direction) and aisle(X-direction) walls. Velocity and impulse histories at the center of the relocatable and aisle walls on the floor are depicted.

A view of the displaced and deformed structures are shown for selected cases. As a standard feature in AUTODYN-3D, such plots can be displayed in rapid succession to create an animated picture of the dynamic event.

6. Conclusions

AUTODYN-3D provides an effective and powerful analysis tool for studying the consequences of the detonation of various configurations of stored ordnance. The calculations were effectively performed without the use of a supercomputer to provide results for the blast loadings, deformations and translational movement of relocatable and aisle walls.

The interactive AUTODYN-3D analysis environment allows the analyst to rapidly setup, analyze, and display the results. The results of the calculations coupled with selected tests ultimately will allow optimization of the HPM design and potential reduction of the land area required by Explosive Safety Quantity Distance (ESQD) arcs.

Figure 8. Z-momentum in Relocatable Wall, Cases 1-5

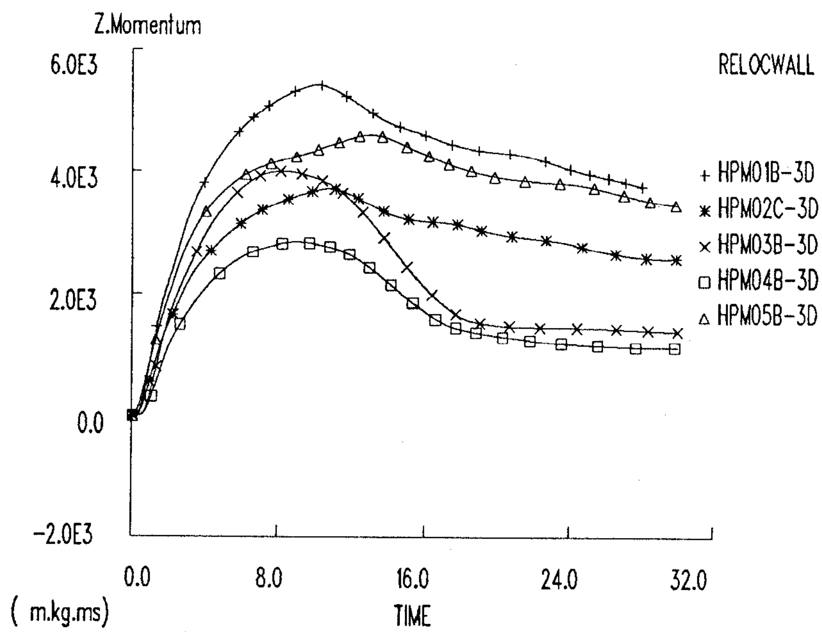

Figure 8. Z-momentum in Relocatable Wall, Cases 1-5

Figure 9. X-momentum in Aisle Wall, Cases 1-5

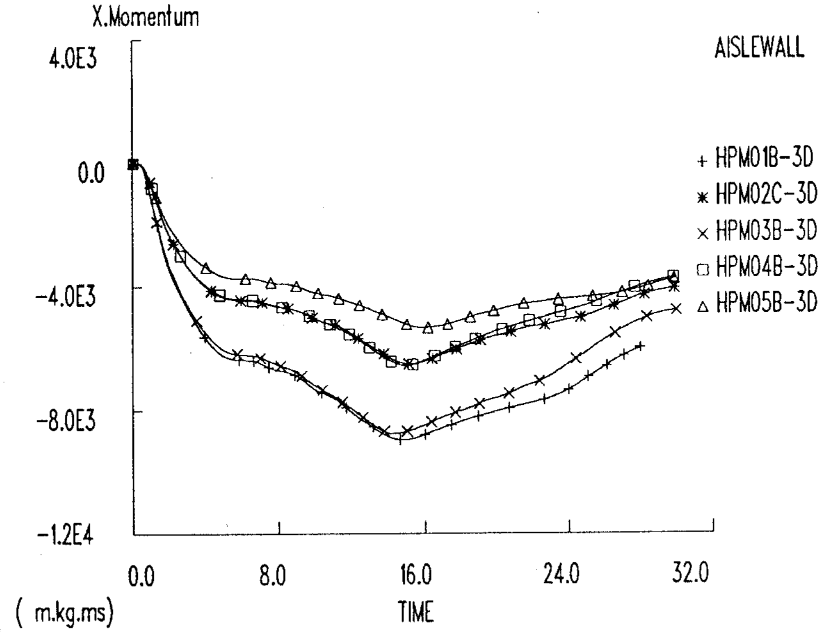

Figure 9. X-momentum in Aisle Wall, Cases 1-5

Figure 10: Z-velocity at base of Relocatable Wall Cases 1-5

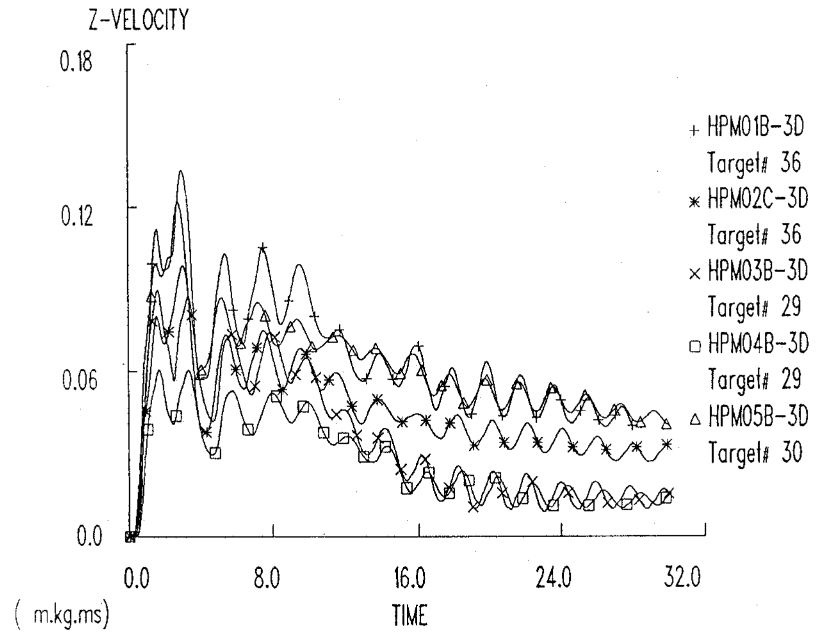

Figure 10: Z-velocity at base of Relocatable Wall Cases 1-5

Figure 11. X-velocity at base of Aisle Wall, Cases 1-5

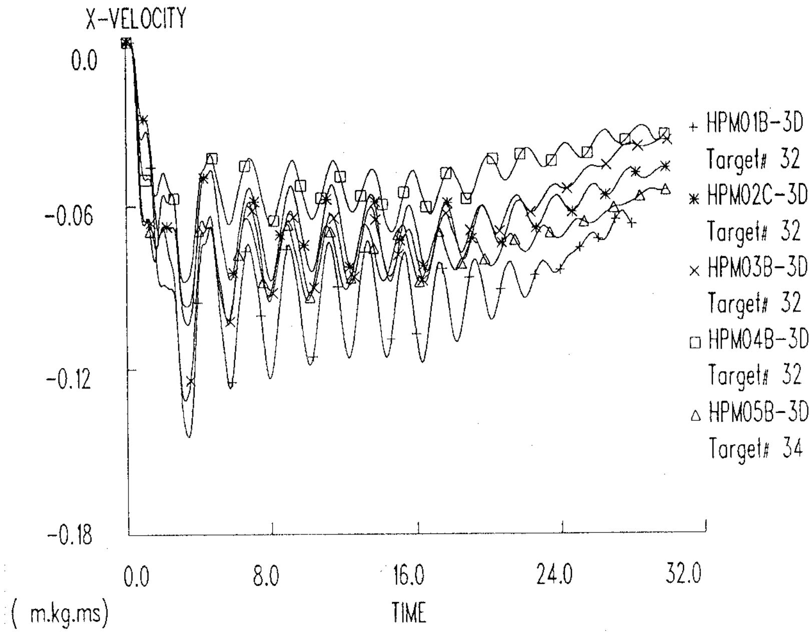

Figure 11. X-velocity at base of Aisle Wall, Cases 1-5

Figure 12. Impulse histories at base of Relocatable Wall, Cases 1-5

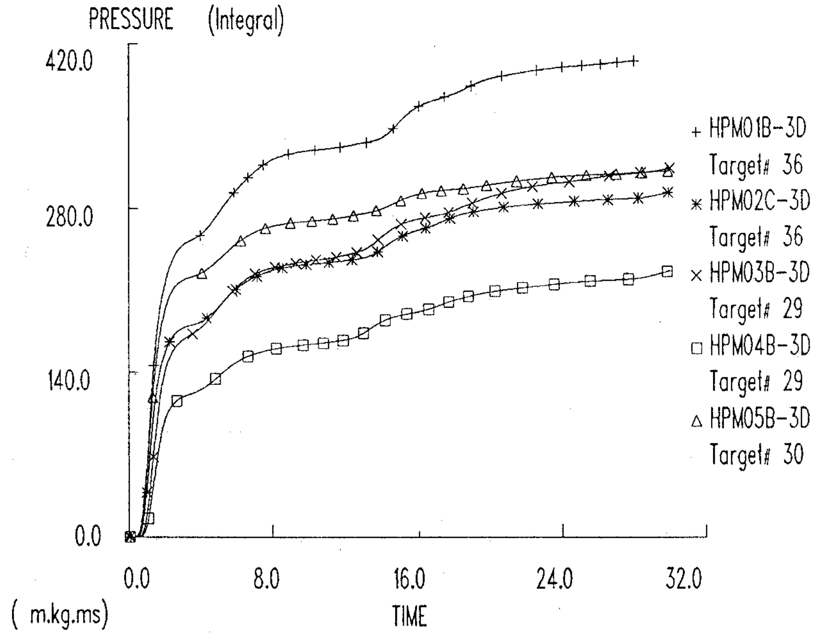

Figure 12. Impulse histories at base of Relocatable Wall, Cases 1-5

Figure 13. Impulse histories at base of Aisle Wall, Cases 1-5

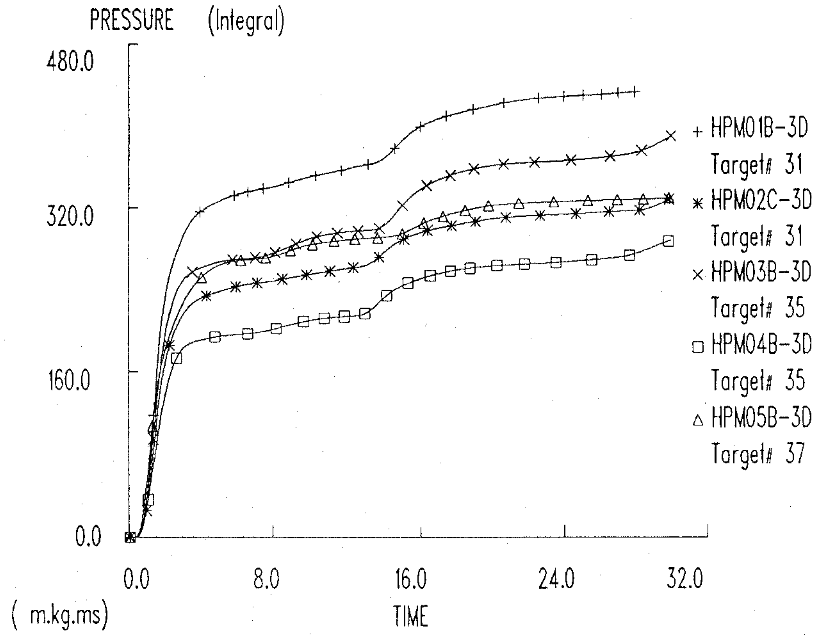

Figure 13. Impulse histories at base of Aisle Wall, Cases 1-5

Figure 14. Plot of displaced structures, Case 1

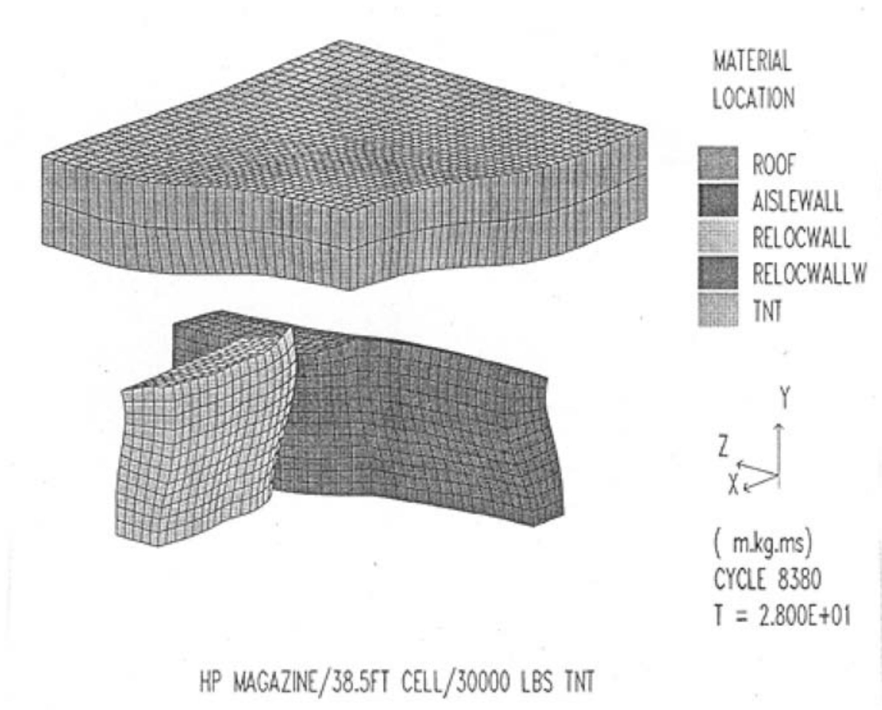

Figure 14. Plot of displaced structures, Case 1

Figure 15. Plot of displaced structures Case 3

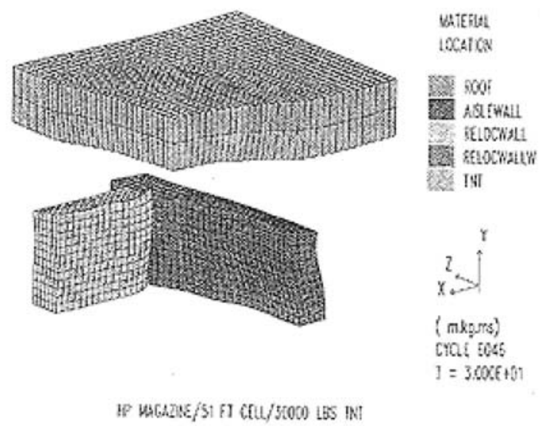

Figure 15. Plot of displaced structures Case 3

Figure 16. Contour plot of pressure, Case 1 at intermediate time

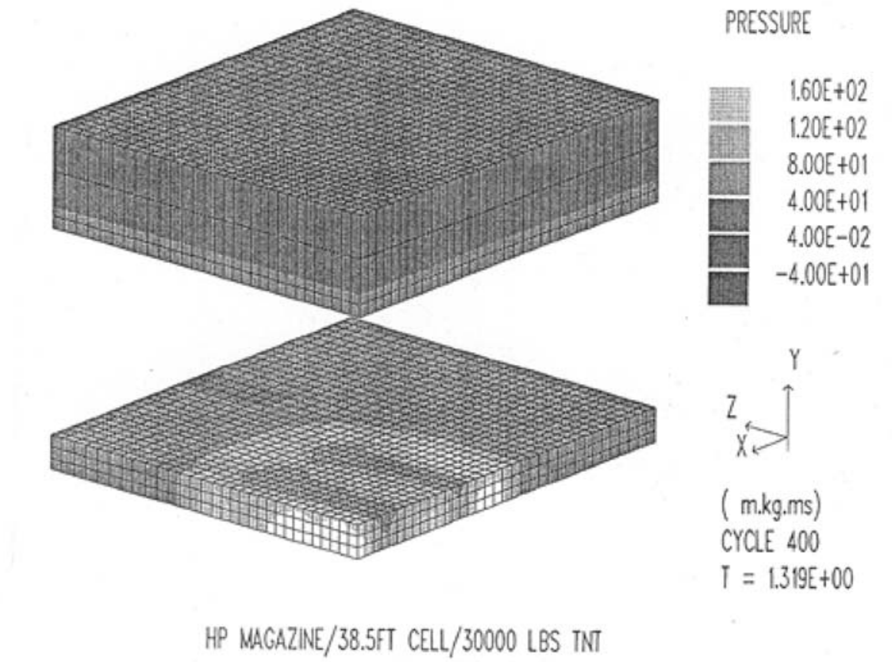

Figure 16. Contour plot of pressure, Case 1 at intermediate time

Appendix: Material Models and Initial Conditions

Material models (units kg-m-msec):

	ROOF	AISLEWALL	RELOCWALL	RELOCWALLW
Equation of state	Linear	Linear	Linear	Linear
Strength model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	None
Reference density	1557.1	1733.63	1605.21	1605.21
Equivalent areal density	970 (lbs/ft^2)	810 (lbs/ft^2)	750 (lbs/ft^2)	750 (lbs/ft^2)
Bulk modulus	6000	6000	6000	6000
Shear Modulus	240	240	240	n/a
Strength model parameters				n/a
P1	0	0	0	
P2	10.976	10.976	10.976	
P3	10E5	10E5	10E5	
P4	0	0	0	
Y1	2	2	2	
Y2	20	20	20	
Y3	20	20	20	
Y4	0	0	0	

TNT / Air Equation of state and initial conditions:

TNT / Air Equation of state and initial conditions:

	TNT	AIR
Equation of state	JWL	JWL
Strength model	None	None
Reference density	1630	1630
Initial density	from 1D remap	1.225
Initial energy	from 1D remap	2.332
Parameter A	3.7377E5	3.73377E5
Parameter B	3.7471E5	3.7471E5
Parameter R1	4.15	4.15
Parameter R2	.9	.9
Parameter W	.35	.35 *
C-J Detonation velocity	6.93	n/a
C-J Energy / unit volume	6000	n/a
C-J Pressure	2.1E4	n/a

* equivalent to ideal gas constant (gamma) = 1.35

References:

1. Lee et al, “JWL Equation of State Coefficients for High Explosives”, Lawrence Livermore Lab, January 1973, UCID-16189.

2. AUTODYN-2D Euler Remapping Tutorial, Century Dynamics, Inc. 1993.

3. AUTODYN-3D Users Manual, Century Dynamics, Inc. 1994.